

Cosmic Background Radiation and ‘ether-drift’ experiments

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PACS 98.70.Vc – Background radiations

PACS 07.60.Ly – Interferometers

PACS 89.75.Fb – Structures and organization in complex systems

Abstract. - ‘Ether-drift’ experiments have played a crucial role for the origin of relativity. Though, a recent re-analysis shows that those original measurements where light was still propagating in gaseous systems, differently from the modern experiments in vacuum and in solid dielectrics, indicate a small universal anisotropy which is naturally interpreted in terms of a non-local thermal gradient. We argue that this could possibly be the effect, on weakly bound gaseous matter, of the temperature gradient due to the Earth’s motion within the Cosmic Background Radiation (CBR). Therefore, a check with modern laser interferometers is needed to reproduce the conditions of those early measurements with today’s much greater accuracy. We emphasize that an unambiguous confirmation of our interpretation would have far reaching consequences. For instance, it would also imply that all physical systems on the moving Earth are exposed to a tiny energy flow, an effect that, in principle, could induce forms of self-organization in matter.

Premise. – Over the years, particular efforts have been devoted to improve the sensitivity of those ‘ether-drift’ experiments which look for the possible existence of a preferred reference frame through an anisotropy of the two-way velocity of light $\bar{c}_\gamma(\theta)$ (for a general review see e.g. [1]). This is the only one that can be measured unambiguously and is defined in terms of the one-way velocity $c_\gamma(\theta)$ as

$$\bar{c}_\gamma(\theta) = \frac{2 c_\gamma(\theta) c_\gamma(\pi + \theta)}{c_\gamma(\theta) + c_\gamma(\pi + \theta)} \quad (1)$$

Here θ represents the angle between the direction of light propagation and the Earth’s velocity with respect to a hypothetical preferred frame Σ . By defining the anisotropy

$$\Delta\bar{c}_\theta = \bar{c}_\gamma(\pi/2 + \theta) - \bar{c}_\gamma(\theta) \quad (2)$$

the most recent result from Nagel et al. [2] amounts to a fractional accuracy $(|\Delta\bar{c}_\theta|/c) \lesssim 10^{-18}$. With this new measurement, by looking at their Fig.1 where all ether-drift experiments are reported, one gets the impression of a steady, substantial improvement over the original 1887 Michelson-Morley [3] result $(|\Delta\bar{c}_\theta|/c) \lesssim 10^{-9}$.

Though, this first impression might be misleading. The various measurements were performed in different conditions, i.e. with light propagating in gaseous media (as in

[3–6]) or in a high vacuum (as in [7–9]) or inside dielectrics with a large refractive index (as in [2,10]) and there could be physical reasons which prevent such a straightforward comparison. In this case, the difference between old experiments (in gases) and modern experiments (in vacuum or solid dielectrics) might not depend on the technological progress only but also on the different media that were tested.

Another possible objection concerns the traditional analysis of the data. The model assumed so far of slow, periodic time modulations, associated with the Earth’s rotation and its orbital revolution, derives from simple spherical trigonometry. Here, there might be a logical gap. The relation between the macroscopic Earth’s motion and the microscopic propagation of light in a laboratory depends on a complicated chain of effects and, ultimately, on the physical nature of the vacuum. By comparing with the motion of a body in a fluid, the standard view corresponds to a form of regular, laminar flow where global and local velocity fields coincide. However, some arguments (for a list of references see [11]) suggest that the vacuum might rather resemble a turbulent fluid where large-scale and small-scale flows are only indirectly related. In this other perspective, the macroscopic Earth’s motion could just give the order of magnitude by fixing the

typical boundaries for a microscopic velocity field which is irregular and intrinsically non deterministic. Although it cannot be computed exactly, one could still estimate its statistical properties by numerical simulations [11,12]. To this end, one could assume forms of turbulence or intermittency which, as in most models, become statistically isotropic at small scales. This could easily explain the irregular character of the data because, whatever the macroscopic Earth's motion, the average of all vectorial quantities (such as the Fourier coefficients extracted from a fit to the temporal sequences in modern experiments or the fringe shifts of the old experiments) would tend to zero by increasing more and more the statistics. In this framework, is not surprising that from an instantaneous signal of given magnitude one ends up with smaller and smaller averages. This trend, by itself, might not imply that there is no physical signal.

Now, by taking into account these two ingredients, namely a) the specificity of the various media and b) the possibility of a genuine, but irregular, physical signal, there are substantial changes in the interpretation of the experiments. We believe that the main conclusions of this re-analysis, and the possible ultimate implications, are sufficiently important to be summarized in a concise form and thus brought to the attention of a wide audience.

CBR and ether-drift experiments. — Let us first observe that the discovery of an anisotropy of the Cosmic Background Radiation (CBR) [13,14] has introduced an important new element. Indeed, the standard interpretation of its dominant dipole component (the CBR kinematic dipole [15]) is in terms of a Doppler effect due to the motion of the solar system with average velocity $v \sim 370$ km/s toward a point in the sky of right ascension $\alpha \sim 168^\circ$ and declination $\delta \sim -7^\circ$. This makes the existence of a preferred reference frame more than a simple possibility.

In spite of this, it is generally assumed that this motion cannot be detected in a laboratory by optical measurements. This belief derives precisely from the ether-drift experiments, at least when interpreted as a long sequence of 'null results' with better and better systematics. Still, over the years, greatest experts [4,16] have seriously questioned the traditional null interpretation of the early experiments. In their opinion, the small residuals should not be neglected. To have an idea of their magnitude, let us recall that, at the beginning, the fringe shifts produced by the rotation of the interferometers were analyzed by using the classical formula

$$(\Delta\lambda/\lambda)_{\text{class}} \sim (L/\lambda)(v^2/c^2) \quad (3)$$

where v is the projection of the Earth's velocity in the plane of the interferometer, L the length of the optical path and λ the light wavelength. Quantitatively, the very early measurements are summarized in Fig.1 (from ref. [4]) where the velocities obtained with Eq.(3) in various experiments are reported and compared with a smooth curve fitted by Miller to his own results as function of

the sidereal time. These experimental velocities, lying in the range $7 \div 10$ km/s, imply that the fringe shifts in the various experimental sessions were about $10 \div 20$ times smaller than those expected classically for the Earth's orbital value $v = 30$ km/s (the minimum anticipated drift velocity).

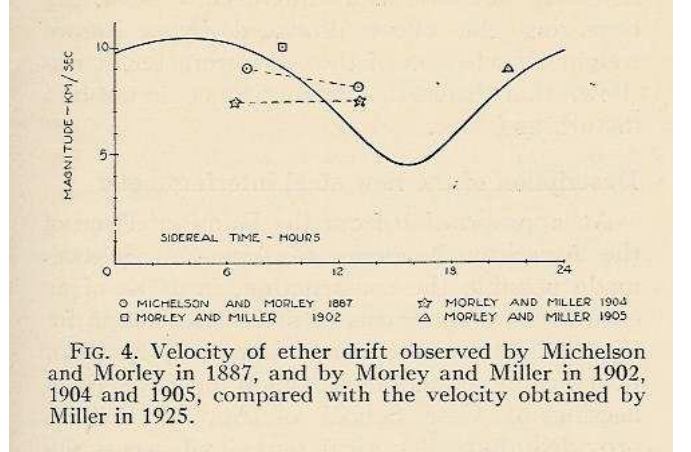


Fig. 1: The velocities obtained with Eq.(3) in various experiments, as reported by Miller [4].

At the same time, although much smaller than the expected value, the measured fringe shifts were often non negligible [4,12] as compared to the extraordinary accuracy of the interferometers. This suggests that, in some alternative framework, the small, and irregular, effects could acquire a definite physical meaning. So far, their interpretation has been in terms of unimportant, mainly thermal, disturbances. However, what about a 'non-local' temperature effect? An observer moving through the CBR would see different temperatures in different directions and, in this case, the situation could change completely. This also suggests to concentrate the attention on the experiments in gaseous systems because the elementary constituents of such weakly bound matter can be set in motion by extremely small thermal gradients.

To estimate this effect, let us recall that, due to the motion of an observer with velocity v , a pure black-body spectrum of temperature T_o becomes Doppler shifted in the various directions θ according to the relation ($\beta = v/c$)

$$T(\theta) = \frac{T_o \sqrt{1 - \beta^2}}{1 - \beta \cos \theta} \quad (4)$$

Therefore, if one sets $T_o \sim 2.7$ K and $\beta \sim 0.0012$ as for $v = 370$ km/s, there is an angular variation

$$\Delta T(\theta) \sim T_o \beta \cos \theta \sim \pm 0.003 \text{ K} \quad (5)$$

A more accurate estimate for an ether-drift experiment would first require to replace the value $v = 370$ km/s with its projection in the plane of the interferometer and then evaluate the effects on the observation site. We have not attempted this non-trivial task. However, for Miller's

Table 1: *The average velocity observed (or the limits placed) by the classical ether-drift experiments in the alternative interpretation where the fringe shifts are given by Eq.(6) and the relation between the observable v_{obs} and the kinematical v is governed by Eq.(7). For the dots in the Michelson-Pease-Pearson case we address the reader to ref. [12].*

Experiment	gas in the interferometer	v_{obs} (km/s)	v (km/s)
Michelson-Morley(1887)	air	$8.4^{+1.5}_{-1.7}$	349^{+62}_{-70}
Morley-Miller(1902-1905)	air	8.5 ± 1.5	353 ± 62
Kennedy(1926)	helium	< 5	< 600
Illingworth(1927)	helium	3.1 ± 1.0	370 ± 120
Miller(1925-1926)	air	$8.4^{+1.9}_{-2.5}$	349^{+79}_{-104}
Michelson-Pease-Pearson(1929)	air	$4.5 \pm \dots$	$185 \pm \dots$
Joos(1930)	helium	$1.8^{+0.5}_{-0.6}$	330^{+40}_{-70}

observations this analysis was carried out by Kennedy, Shankland (see p.175 of [17], in particular the footnote¹⁶) and Joos [18]. Their conclusion was that periodic temperature variations of about ± 0.001 K or ± 0.002 K in the air of the optical arms could be responsible for Miller’s average fringe pattern. Now, on the one hand, these temperature values agree well with Eq.(5). On the other hand, such interpretation of the residual effects would also fit with Miller’s conclusion [19] that the needed temperature variations could not be due to a uniform heating (or cooling) of the laboratory but should have been those produced by a directional effect, as it would be with the CBR dipole.

With this premise, it becomes important to check if the small residuals indicate a non-local phenomenon that could be interpreted as a universal temperature gradient. To this end, we summarize in Table 1 the main results of ref. [12] which represents the most complete analysis performed so far of the classical experiments in gaseous media (Michelson-Morley [3], Miller [4], Illingworth [5], Joos [6]...). For the typical projections v associated with an Earth’s velocity of 370 km/s, by introducing the gas refractive index $\mathcal{N} = 1 + \epsilon$, the experimental fringe shifts produced by the rotation of the interferometers were found to scale as

$$(\Delta\lambda/\lambda)_{\text{EXP}} \sim (L/\lambda)(v_{\text{obs}}^2/c^2) \quad (6)$$

with an ‘observable’ velocity

$$v_{\text{obs}}^2 \sim 2\epsilon v^2 \quad (7)$$

Notice that the effect vanishes in the $\epsilon \rightarrow 0$ limit, as expected when the velocity of light c_γ approaches the basic parameter c entering Lorentz transformations. Thus one gets $(v_{\text{obs}}^2/c^2) \lesssim 10^{-9}$ for air at atmospheric pressure, where $\mathcal{N} \sim 1.00029$, or $(v_{\text{obs}}^2/c^2) \lesssim 10^{-10}$ for helium at atmospheric pressure, where $\mathcal{N} \sim 1.000035$. To appreciate the strong suppression effect, one should compare with the corresponding classical prediction Eq.(3). For instance, for air, the fringe shifts for $v = 370$ km/s are about 10 times smaller than those expected classically for the much lower velocity $v = 30$ km/s. For gaseous helium, the effect is even 100 times smaller. We believe that the

good agreement among the various determinations of v in Table 1 provides enough evidence for the existence of a non-local effect that should be understood.

Derivation of the observed anisotropy. – Within the traditional thermal interpretation, the ultimate explanation of the observed universal anisotropy proportional to $\epsilon(v/c)^2$ was searched for [12, 20] in the fundamental energy flow which, on the basis of general arguments, is expected in a quantum vacuum which is not exactly Lorentz invariant and thus sets a preferred reference frame. However, the agreement between Eq.(5) and the old estimates of Joos, Kennedy and Shankland introduces now a new argument and provides the most natural interpretation in terms of the CBR itself.

To try to understand Eqs.(6) and (7), one can first start from standard assumptions, namely:

i) light anisotropy should vanish when both the observer and (the container of) the medium where light propagates are taken at rest in the hypothetical preferred frame Σ , for instance the system where the CBR looks exactly isotropic

ii) light anisotropy should also vanish if light propagates in an ideal vacuum, i.e. for a medium refractive index $\mathcal{N} = 1$ so that c_γ coincides with c

This means that, in the physical case where instead both the observer and (the container of) the medium are at rest in the laboratory S' frame, any possible anisotropy should vanish identically in the limit of velocity $v = 0$ when $S' \equiv \Sigma$. Therefore, if we restrict our analysis to the region $\mathcal{N} = 1 + \epsilon$ of gaseous media, one can expand in the two small parameters $\beta = v/c$ and $\epsilon = \mathcal{N} - 1$. Then, any possible anisotropy will start to $\mathcal{O}(\epsilon\beta)$ for the one-way velocity $c_\gamma(\theta)$ and to $\mathcal{O}(\epsilon\beta^2)$ for the two-way velocity $\bar{c}_\gamma(\theta)$ which, by its very definition, is invariant under the replacement $\beta \rightarrow -\beta$. At the same time, for any fixed β , $\bar{c}_\gamma(\theta)$ is also invariant under the replacement $\theta \rightarrow \pi + \theta$. Thus, to lowest non-trivial level $\mathcal{O}(\epsilon\beta^2)$, one finds the general expression

$$\bar{c}_\gamma(\theta) \sim \frac{c}{\mathcal{N}} \left[1 - \epsilon\beta^2 \sum_{n=0}^{\infty} \zeta_{2n} P_{2n}(\cos\theta) \right] \quad (8)$$

Here, to account for invariance under $\theta \rightarrow \pi + \theta$, the angular dependence has been given as an infinite expansion of even-order Legendre polynomials with arbitrary coefficients $\zeta_{2n} = \mathcal{O}(1)$.

A crucial point for the thermal interpretation is that Eq.(8) admits a dynamical basis. In fact, exactly the same form is obtained [12] (see also Appendix 1 of [20]) if, in the S' frame, there were convective currents of the gas molecules associated with an Earth's absolute velocity v . Both derivations clearly differentiate gaseous systems from solid and liquid dielectrics (where instead \mathcal{N} differs substantially from unity) and, therefore, one can understand the difference with strongly bound matter, as in the Shamir-Fox experiment [10]. Being aware that the classical measurements could be proportional to $\epsilon(v/c)^2$, they selected a medium where the effect of the refractive index would have been enhanced (i.e. perspex where $\mathcal{N} \sim 1.5$). Since this enhancement was not observed, they concluded that the experimental basis of special relativity was strengthened. However, with a thermal interpretation, one can reconcile the different behaviors because in solid dielectrics a small temperature gradient would mainly dissipate by heat conduction without generating any appreciable particle motion or light anisotropy in the rest frame of the apparatus.

Now, Eq.(8) is exact to the given accuracy and predicts the right order of magnitude $\epsilon(v/c)^2$ of the observed anisotropy. Therefore, by leaving out the first few ζ' s as free parameters in the fits, one could directly compare with the experimental data. Still, there is one more derivation of the $\epsilon \rightarrow 0$ limit with a preferred frame which, on the basis of other symmetry arguments, permits to get rid of the unknown coefficients in (8) and to deduce Eqs.(6) and (7). The reason is that the transformation matrix which connects the space-time metric $g^{\mu\nu}$ for light propagation in the laboratory S' frame to the reference isotropic metric $\gamma^{\mu\nu} = \text{diag}(\mathcal{N}^2, -1, -1, -1)$ in the preferred Σ frame, is a two-valued function for $\mathcal{N} \rightarrow 1$. As shown in Appendix 2 of ref. [20], by taking into account this subtlety, there are two solutions: either $g^{\mu\nu} = \gamma^{\mu\nu}$ or $g^{\mu\nu} \sim \eta^{\mu\nu} + 2\epsilon u^\mu u^\nu$ where $\eta^{\mu\nu}$ is the Minkowski tensor and u^μ the dimensionless S' 4-velocity. With the latter choice, from the condition $p_\mu p_\nu g^{\mu\nu} = 0$, by defining $c_\gamma(\theta)$ from the ratio $p_0/|\mathbf{p}|$ and using Eq.(1), one finds a two-way velocity

$$\bar{c}_\gamma(\theta) \sim (c/\mathcal{N}) [1 - \epsilon\beta^2 (2 - \sin^2 \theta)] \quad (9)$$

which corresponds to setting in Eq.(8) $\zeta_0 = 4/3$, $\zeta_2 = 2/3$ and all $\zeta_{2n} = 0$ for $n > 1$. Eq.(9) is a definite realization of the general structure in (8) and provides a partial answer to the problem of calculating the ζ' s from first principles. As such, it represents a model to compute the time difference for light propagation back and forth at right angles along rods of length L (at rest in the S' frame)

$$\Delta t(\theta) = (2L/\bar{c}_\gamma(\theta)) - (2L/\bar{c}_\gamma(\pi/2 + \theta)) \sim (2L/c)(\Delta\bar{c}_\theta/c) \quad (10)$$

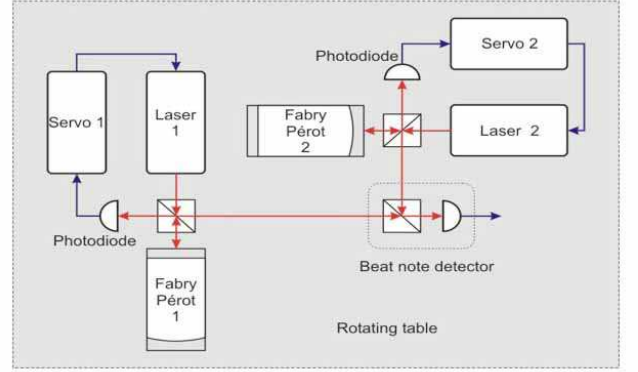


Fig. 2: The scheme of a modern ether-drift experiment. The light frequencies are first stabilized by coupling the lasers to Fabry-Pérot optical resonators. The frequencies ν_1 and ν_2 of the signals from the resonators are then compared in the beat note detector which provides the frequency shift $\Delta\nu = \nu_1 - \nu_2$. In present experiments a very high vacuum is maintained within the resonators.

This gives back the phenomenologically successful Eqs.(6) and (7). All together, we have found a consistent description of the data where symmetry arguments, on the one hand, motivate and, on the other hand, find justification in underlying dynamical mechanisms.

Conclusions and outlook. — This overall level of consistency requires a check with a new generation of precise laser interferometers in order to reproduce the experimental conditions of the old experiments with today's much greater accuracy. The essential ingredient is that the optical resonators that nowadays are coupled to the lasers should be filled by gaseous media, see Fig.2. Such a type of 'non-vacuum' experiments would be along the lines of ref. [21] where just the use of optical cavities filled with different materials was considered as a useful complementary tool to study deviations from exact Lorentz invariance. The only delicate aspect concerns the high relative stability in temperature and pressure of the two cavities which is required to prevent possible spurious sources of the frequency shifts. However, with present technology and technical skill ¹, this should not represent a too serious problem.

In units of their natural frequency ν_0 , we then predict a frequency shift between the two resonators

$$(\Delta\nu/\nu_0)_{\text{gas}} = (\Delta\bar{c}_\theta/c)_{\text{gas}} \sim (\mathcal{N}_{\text{gas}} - 1) (v^2/c^2) \quad (11)$$

which should be larger by orders of magnitude than the corresponding effect with vacuum resonators [7]–[9]. This substantial enhancement is confirmed by the only modern

¹For instance, an important element to increase the overall stability and minimize systematic effects may consist in obtaining the two optical resonators from the same block of material as with the crossed optical cavity of ref. [22].

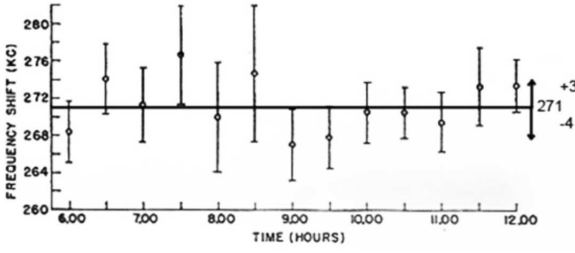


Fig. 3: The frequency shifts of ref. [23]. The double arrow indicates the overall variation, with respect to the constant value, expected in the same model Eqs.(9) and (11) used for the classical experiments. To this end, we have assumed the range $v \sim 320_{-60}^{+45}$ km/s, as for the average CBR Earth’s motion at the latitude of Boston. In this way, once the shift for the average velocity 320 km/s is hidden in the much larger spurious frequency shift, the two relative variations of +3 kHz and -4 kHz would correspond respectively to $v = 365$ and $v = 260$ km/s.

experiment that has been performed in similar conditions: the 1963 MIT experiment by Jaseja et. al [23]. They were looking at the frequency shift of two orthogonal He-Ne lasers placed on a rotating platform. For a proper comparison, one has to subtract preliminarily a large systematic effect of about 270 kHz interpreted as being due to magnetostriction. As suggested by the same authors, this spurious effect, that was only affecting the normalization of the experimental $\Delta\nu$, can be subtracted by looking at the variations of the data. In this case, for a laser frequency $\nu_0 \sim 2.6 \cdot 10^{14}$ Hz, the residual variations of a few kHz, see Fig.3, are roughly consistent with the refractive index $\mathcal{N}_{\text{He-Ne}} \sim 1.00004$ and the typical variations of the Earth’s velocities in Table 1.

To conclude, suppose some future experiment would confirm the unambiguous detection in gaseous systems of a universal signal as given by Eq.(11). This could have other non-trivial implications. In fact, it would mean that all physical systems on the moving Earth are exposed to a tiny energy flow, an effect which, in principle, could induce forms of spontaneous self-organization in matter [24,25]. In slightly different terms, the existence of such a flow introduces a weak, residual form of ‘noise’ which is intrinsic to natural phenomena (‘objective noise’ [26]). This could be crucial because it has becoming more and more evident that many classical and quantum systems can increase their efficiency thanks to the presence of noise (e.g. photosynthesis in sulphur bacteria [27], quantum transport [28], protein crystallization [29], noise enhanced stability [30] or stochastic resonance [31]). In this sense, a fundamental signal with genuine characters of turbulence or intermittency could be thought as the microscopic origin of macroscopic aspects such as self-organized criticality, large-scale fluctuations, fat-tailed probability density functions among many others, which characterize the behavior of many complex systems, see e.g. [32–35].

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